

Effects of Current Density and Nickel as an Impurity on Zinc Electrowinning

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Abstract

The effects of current density and nickel as an impurity on zinc electrowinning has been studied to find an optimum current density to solve the zinc re-dissolution problem due to a high level of nickel in electrolyte. In the presence of 0.4 mg/L Ni, with increasing current density from 450 to 550 and 650 to 750 Am⁻², the average induction time for zinc re-dissolution decreased from 47.2 to 44.62 and 44.41 to 40.28 hours, the average current efficiency decreased from 93.74 to 93.56 and 93.34 to 92.93%, and the energy consumption increased from 2.916 to 2.977 and 2.988 to 3.077 kwh/kg Zn. The zinc deposit masses at 550, 650 and 750 Am⁻² were 10.6, 32.6 and 35.6% greater than that at 450Am⁻² respectively. Considering the energy consumption and zinc deposit mass, a current density of 650 Am⁻² is recommended for zinc electrowinning. The zinc electrowinning time should be slightly shorter than the induction time. At this current density, the zinc deposit mass can be significantly increased while the energy consumption increases slightly. In some plant operations, if the cost for removal of nickel to a satisfactory level is too expensive, the current density can be adjusted to maximize the zinc deposit mass. The presence of 0.4 mg/L Ni has very little effect on cathodic polarization behaviour.

Keywords

Zinc Electrowinning; Induction Time; Sulfate Solution; Nickel

Introduction

Zinc electrowinning which is generally conducted in acidic sulfate solution has been extensively studied to improve the zinc current efficiency and reduce energy consumption [Alfantazi and Dreisinger, 2001; Recendiz et al., 2007; Tripathy et al., 2004]. The zinc current efficiency and deposit quality are affected by zinc and sulfuric acid concentrations, current density, temperature and impurities. Some of the harmful impurities such as copper and iron can be easily removed to such an extent that they virtually do not affect zinc deposition. However, some of them such as

cobalt and nickel are not easily removed.

In the presence of impurities such as Sb, Co, Ni, As, Ge, the zinc current efficiency was significantly decreased and the quality of zinc deposit was poor [Ault and Frazer, 1988; Robinson and O'Keefe, 1976]. With regard to cathode deposit behaviour, a general statement can be made to the effect that the ions of those impurities with standard potentials more negative than zinc, such as Al, Mg, Ca and Na, have little effect; ions of impurities that are marginally more positive than zinc, such as Cd, and Pb, tend to deposit at the cathode, decreasing its purity; ions of those metals that are much more positive than zinc and are characterized with low hydrogen overpotential such as Pt, Ag, Fe, Co, Ni and Cu decrease current efficiency [Robinson and O'Keefe, 1976].

During zinc electrowinning from sulfate electrolytes containing nickel, a process of re-dissolution of deposited metal takes place [Mackinnon and Morrison, 1986; Stefanov and Ivanov, 2002; Mackinnon et al., 1987; Ivanov, 2004]. The term "induction time or period" is used in zinc electrowinning [Turomshina and Stender, 1955; Fosnach and O'Keefe, 1980; Jaksic, 1986]. During this induction time, which coincides with the beginning of zinc electrodeposition, the zinc deposits are uniform and adhere firmly to the cathode. The typical current efficiency is 93-95%. Following this induction time, zinc re-dissolution occurs with hydrogen evolution. After the zinc is completely dissolved, deposition restarts. The induction time depends on several factors such as temperature, cathodic current density, and the concentrations of sulfuric acid, zinc and impurities. The local pair model is often used to explain the re-dissolution of zinc deposit [Ivanov, 2004; Turomshina and Stender, 1955; Wang and O'Keefe, 1980; Fratesi et al., 1979; Wark, 1979]. The metal impurities co-deposited with zinc

behave as a cathode with respect to the zinc deposit and catalyzes the hydrogen discharge. However, the induction time is only observed in the presence of iron-group metal impurities. The overpotential of hydrogen evolution on nickel is about 0.6 V lower than that on zinc [Sharma, 1998]. Nickel can dramatically depolarize the discharge of hydrogen ions. The induction time is related to the hydrogen bubble formation stage on the active regions of the cathode surface, containing codeposited nickel [Maja et al., 1982; Wiart et al., 1990; Cachet et al., 1993; Bozhkov et al., 1990].

A high current efficiency and high quality zinc deposit can be obtained from highly purified electrolyte. However, rigorous electrolyte purification can be economically nonviable. Alternative ways to reduce the harmful effects of impurities are: (1) the use of suitable additives, (2) the optimization of zinc electrowinning operating conditions, or (3) the combination of (1) and (2).

The objective of this study was to find an optimum current density and zinc deposition time to suppress or avoid the harmful effect of nickel and optimize zinc electrowinning operation by studying the influence of nickel ions and current density on current efficiency and induction time for zinc electrowinning from sulfate electrolytes.

Experimental

Mini-Cells for Zinc Electrowinning

The anodes and cathodes were manufactured using lead-silver alloy and an industrial aluminium sheet for zinc electrowinning. The non-working areas of the anodes and cathodes were surrounded with a cold-mount epoxy resin. A copper wire was connected to an anode or cathode using a silver-rich conductive cement for the electrical connection. The sizes of the anodes and cathodes were 1×1 cm². The electrolysis cell was a 600-mL Pyrex beaker fitted with a lid in which spacers were drilled to maintain a fixed anode-cathode distance (20 mm). The electrolyte volume was set at 500 mL. After each test, the zinc deposit was stripped and the aluminum cathode was brushed using an abrasive cleaning pad. Both the cathode and anode were rinsed with de-ionized water and stored in a dry, clean place for the next test.

Electrochemical Conditioning of Lead Anodes

New lead anodes were first sandblasted to achieve an average roughness of 30 μm, and then

electrochemically conditioned for 3 weeks. The objective of sandblasting and electrochemical conditioning was to build a dense PbO₂ layer and also a dense layer of MnO₂, both of which firmly adhere to the lead substrate. These two layers prevent the significant dissolution of lead and contamination of the zinc deposit. If the anodes were not used for a certain time, they were electrochemically re-conditioned. The electrolyte was prepared using neutral zinc electrolyte, deionized water, reagent grade sulfuric acid and highly pure metallic manganese with the composition of 70 g/L Zn, 140 g/L H₂SO₄ and 5 g/L Mn. Seven cycles (2-3 day for one cycle) of zinc electrowinning were applied. At the beginning of each cycle, 5 mg/L of animal bone glue was added to each cell. The electrolyte was not changed for each cycle. The cells were connected in a series for a constant electrical current that was supplied by a PAR273A electrochemical interface. All cells were placed in a water bath and the temperature was controlled at 38± 0.1°C. The cell voltage and current were measured using an OMB-PDQ2 data acquisition module from OMEGA Inc. and a Model 90000-999 DC Ammeter shunt from Canadian Shunt Industries Ltd.

Electrowinning Tests

The composition of the electrolyte was: 55 g/L Zn, 160 g/L H₂SO₄, 2 g/L Mn, 2.5 mg/L Arabic gum and variable amounts of additives. The experiment setup was the same as that for electrochemical conditioning of the lead anodes

Polarization Measurement

Cyclic voltammetry and linear polarization were carried out in a three electrode system using a PAR273A electrochemical interface, where the cell consisted of a lead anode (1×1 cm²) covered with MnO₂, an Al cathode (1×1 cm²) and an Ag/AgCl reference electrode. The anode-cathode distance was 5 cm. Before cathodic polarization, the cathodes were first electrodeposited with an 18 μm thick zinc layer from the same electrolyte used for polarization measurements.

Solution Preparation

Highly pure zinc oxide, reagent grade sulfuric acid and highly pure metallic manganese were used to prepare synthetic electrolyte. The composition of the zinc oxide from USZinc was: 99.87% ZnO, 0.0001% Cd,

0.0001%Fe, 0.125% water, 0.0008% Pb and 0.00001% As. The contents of other heavy metal impurities are not expected to exist (less than 0.0001%). The pure metallic manganese was from Manganese Metal Company, South Africa. Reagent grade nickel sulfate was added as an impurity. The Arabic gum from Sigma Aldrich and bone animal glue from Teck Corporation were used as additives.

Neutral mother electrolyte (160-180 g/L Zn and 5-10 g/L H_2SO_4) was first prepared using sulfuric acid and zinc oxide. The zinc mother solution was prepared using the following procedures: (1) slowly add sulfuric acid to deionized water, (2) gradually add zinc oxide into cooled sulfuric acid solution with stirring, (3) after the solution cools down, strontium carbonate (0.1 g/L) is added to remove lead through co-precipitation of lead sulfate with strontium sulfate with stirring (over one hour), (4) let the solid settle over night, and (5) filter the mother solution to remove the precipitate (SrSO_4).

The electrolyte was prepared by mixing mother solution, deionized water, sulfuric acid and additives.

Chemical Analysis

The concentration of zinc was analyzed by titration with EDTA. In the presence of Mn^{2+} , the titration was calibrated due to the interference of Mn^{2+} . The free acid was titrated using 1 N NaOH.

Results and Discussion

Anode Conditioning and Reproducible Tests

Before the electrowinning tests, the anodes were conditioned several times and reproducibility tests were conducted. The zinc current efficiencies for all twenty cells in the final anode conditioning test were greater than $96.5 \pm 0.4\%$, and those in the reproducibility test were greater than $95.7 \pm 0.15\%$, suggesting the cells were well conditioned and demonstrated good uniformity.

Typical Cell Voltages of Zinc Electrowinning

Fig. 1 shows typical cell voltage vs time curves obtained from the electrolyte containing nickel. The cell voltage first rose rapidly at the beginning due to the larger cathodic polarization on zinc than that on the aluminum substrate. Then it gradually decreased due to the increase in the cathode surface area and hydrogen ion concentration, and the decrease in the cathode-anode distance as more zinc was deposited.

Voltage noise appeared for Cells B and C. The cell voltage sharply dropped for Cells B and D, indicating the occurrence of zinc re-dissolution.

As shown in Fig. 2, the cathode potential vs time curve was smooth and the cell voltage noise resulted from the anode potential noise. The anode potential noise was probably primarily caused by the poor contact between the loosely connected manganese dioxide particles, and that between the manganese dioxide layer and lead substrate. Oxygen evolution in the porous manganese dioxide layer exerted varying forces on the manganese dioxide particles and causes the fluctuation in the contact resistance and thus potential drop. Since the electrolyte contained 2 g/L manganese ions, manganese dioxide accumulated on the anode during zinc electrowinning. As more manganese dioxide was deposited, the manganese dioxide layer became loose and finally fell off the anode.

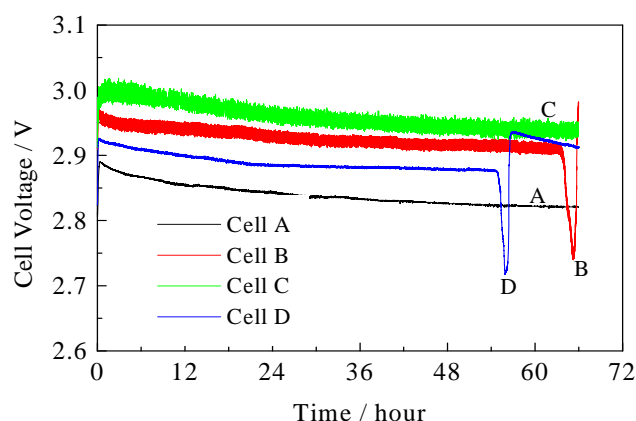


FIG. 1 TYPICAL CELL VOLTAGE VS TIME AT 450 A m^{-2}

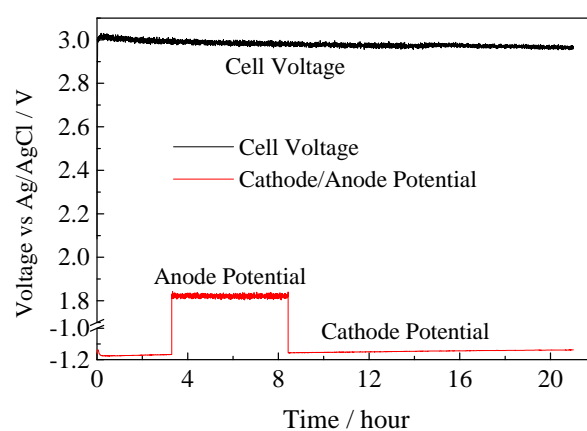


FIG. 2 CELL VOLTAGE, AND ANODE AND CATHODE POTENTIALS VS TIME FOR THE CELL WITH VOLTAGE NOISE AT 450 A m^{-2} .

A rescaled cell voltage vs time curve with zinc re-dissolution is shown in Fig. 3. During the induction time, the cell voltage decreased very slowly. When the nickel-rich area increased to a critical value, the discharge of hydrogen ions was depolarized so significantly that the cathode potential was mainly determined by the discharge of hydrogen ions. As the nickel-rich area increased, the cathode potential increased quickly while the cell voltage decreased. When most of zinc deposit was dissolved, the nickel-rich area shrank and the cathode potential began to decrease. The cell voltage increased until the cathode was completely covered with zinc. The time for zinc re-dissolution and re-covering the cathode with zinc was about two hours. The cell voltage changed by about 0.2 V. The development of zinc re-dissolution differed for each cell, resulting in various voltage-time curves. For some cells, the zinc re-dissolution was slower (Figure 4). The cell voltage changed to a less extent during the zinc re-dissolution.

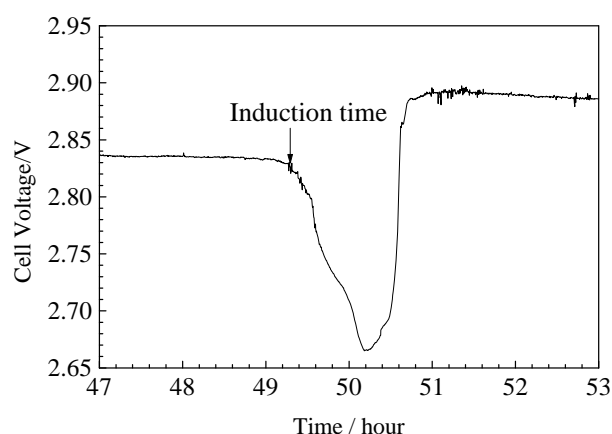


FIG. 3 CELL VOLTAGE VS TIME FOR TYPICAL ZINC RE-DISSOLUTION

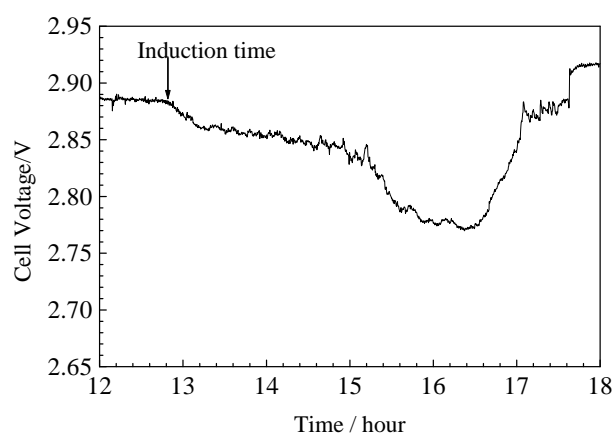


FIG. 4 CELL VOLTAGE VS TIME FOR SLOWER ZINC RE-DISSOLUTION

When the zinc deposit was half re-dissolved (Fig. 5),

the cell voltage was close to its minimum (Fig. 6). By comparison with other cell voltage curves, the cell voltage would increase after 10 to 20 minutes. The zinc re-dissolution started at one site and developed radially.



FIG. 5 ZINC DEPOSIT HALF RE-DISSOLVED

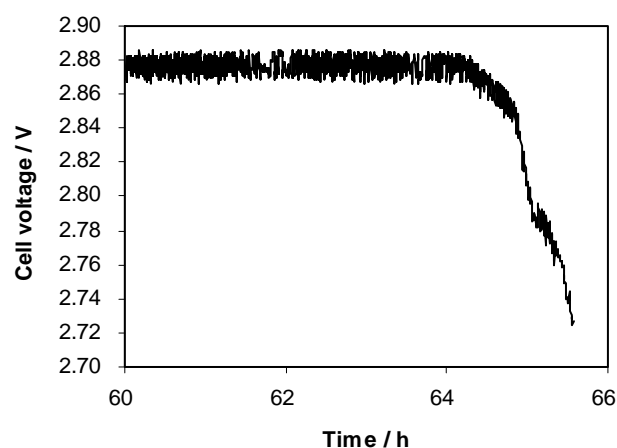


FIG. 6 CELL VOLTAGE VS TIME FOR THE ZINC DEPOSIT HALF RE-DISSOLVED

Effect of Nickel Concentration on Zinc Electrowinning

The effects of nickel concentration on zinc electrowinning were investigated at 0, 0.2 and 0.4 mg/L Ni. The experimental design and results are summarized in Table 1. In Runs 1 and 2, a electrowinning time of 66 hours was used to ensure that zinc re-dissolution occurred for all cells and to study the effect of nickel concentration on the induction time. Zinc deposits had a larger probability of re-dissolution, shorter induction time, and lower current efficiency at a higher nickel concentration.

TABLE 1 RESULTS OF ZINC ELECTROWINNING FROM SULFATE SOLUTION WITH DIFFERENT NICKEL CONTENTS

0 mg/L Ni (Run 1)			0.2 mg/L Ni (Run 2)				0.4 mg/L Ni (Run 3)			
Cell No	Zinc mass (g)	Current efficiency (%)	Cell No	Zinc mass (g)	Current efficiency (%)	Induction time (hour)	Cell No	Zinc mass (g)	Current efficiency (%)	Induction time (hours)
1	3.3625	92.71	2	3.3429	92.68		1	0.4902	13.59	54.79
3	3.3635	92.74	4	0.0097	0.27	63.74	3	0.834	23.12	47.94
5	3.3644	92.76	6	3.3387	92.57		5	0.9391	26.03	45.94
7	3.3673	92.84	8	3.3407	92.62		7	1.0293	28.54	44.32
9	3.3657	92.80	10	0.6827	18.93	50.52	9	1.2013	33.3	40.84
11	3.3555	92.51	12	0	0	63.27	11	0.6203	17.2	52.17
13	3.3515	92.40	14	1.7223	47.75	28.93	13	3.3776	93.64	
15	3.3415	92.13	16	3.3676	93.37		15	1.0433	28.92	44.32
17	3.3546	92.49	18	3.3404	92.61		17	2.7395	75.95	—*
19	3.347	92.28	20	3.3258	92.21		19	0.98	27.17	47.19
Average	3.3574	92.57	Average	2.2471	62.30	51.62	Average	1.3255	36.75	47.19

*Electrowinning time: 66 hours. The induction time for Cell 17 in Run 3 was not determined because of the connection problem with its anode.

The effect of nickel concentration on the current efficiency was investigated in Run 3. Compared with the electrowinning time needed in Run 1 and Run 2, a shorter electrowinning time (20 hours) was required to avoid zinc re-dissolution. This was designed to study the effect of the nickel concentration on current efficiency before re-dissolution occurred. From Table 2, the zinc current efficiency was not affected in the nickel concentration ranging from 0 to 0.4 mg/L.

TABLE 2 EFFECTS OF NICKEL CONCENTRATION ON ZINC CURRENT EFFICIENCY IN RUN 3

Ni (mg/L)	Current efficiency for each cell (%)				Average current efficiency (%)
0	94.14	94.3	94.21	94.25	94.23
0.2	93.57	93.83	94.36	94.08	93.96
0.4	94.37	93.9	94.38	94.25	94.23

*electrowinning time: 20 hours

Effect of Current Density on Induction Time and Current Efficiency

The effects of current density on current efficiency and induction time were investigated in the current density ranging from 450 to 750 Am⁻². Ten cells were used for each current density. The electrowinning time was set to be 66 hours to ensure that re-dissolution took place in all cells.

The induction time for re-dissolution were obtained

based on the cell voltage vs time curves, and then the theoretical zinc mass at the induction time was determined according to the current density. The results are given in Fig. 7. It should be noted that the re-dissolution did not occur for two cells at 550 A m⁻² and one cell at 450 Am⁻². Therefore, the induction time for these three cells was assumed to be 66 hours in order to calculate the average induction time and theoretical zinc mass.

By the increasing current density from 450 to 550 and 650 to 750 Am⁻², the average induction time decreased from 49.28 to 44.62 and 44.41 to 40.28 hours (Fig. 7a) while the theoretical zinc mass at the average induction time increased from 2.693 to 2.983 and 3.586 to 3.682 g (Fig. 7b), indicating that a larger mass of zinc deposit per unit area was able to be obtained at a higher current density. Zinc re-dissolution was primarily caused by the enrichment of nickel on a cathode [Wiat et al., 1990; Cachet et al., 1993]. Since the nickel concentration (0.4mg/L) was much lower than that of zinc (55g/L), and the standard electrode potential of Ni²⁺/Ni (-0.23V vs SHE) is much higher than that of Zn²⁺/Zn(-0.76V vs SHE), nickel was electrodeposited at a limiting current when zinc started electrodeposition. The zinc deposition rate increased with increasing current density while the nickel deposition rate did not change. Therefore, at a higher current density, the nickel content in the deposit was lower and the induction time decreased

much less than that expected in inverse proportion to current density. More zinc was able to be deposited before the re-dissolution at a higher current density.

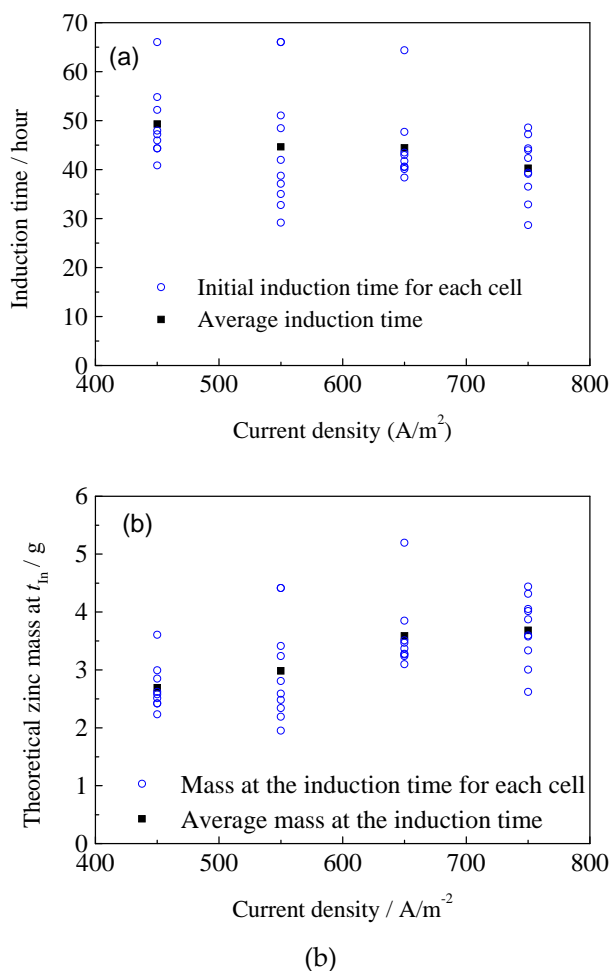


FIG. 7 (a) INDUCTION TIME AND (b) THEORETICAL ZINC MASS AT THE INDUCTION TIME AS A FUNCTION OF CURRENT DENSITY AT 0.4 m/L Ni

Since the electrolyte in a cell was not changed, the zinc concentration decreased faster at a larger current density, resulting in a decrease in the current efficiency if the electrowinning time was close for each current density. Therefore, the amount of electricity passed was set at the same for all current densities and the corresponding electrowinning time was 24, 19.64, 16.62, 14.4 hours for 450, 550, 650 and 750 A/m^2 , respectively.

The current efficiencies were determined based on the masses of zinc deposits and summarized in Fig. 8. With the increasing current density from 450 to 550 and 650 to 750 A/m^2 , the average current efficiency decreased from 93.74 to 93.56 and 93.34 to 92.93%, while the zinc deposit mass increased from 2.524 to 2.791 and 3.347 to 3.422 g, i.e. the zinc deposit masses at 550, 650 and 750 A/m^2 were 10.6%, 32.6% and 35.6%

greater than that at 450 A/m^2 , respectively. The zinc deposit mass increased significantly with increasing current density from 450 to 650 A/m^2 while it increased very little with further increasing current density to 750 A/m^2 . Hydrogen evolution was the main cathodic side reaction. In the current density ranging from 450 to 750 A/m^2 , the current efficiency of hydrogen evolution increased with increasing current density. At a higher cathodic current density, hydrogen evolution was facilitated more than zinc deposition, resulting in a lower zinc current efficiency.

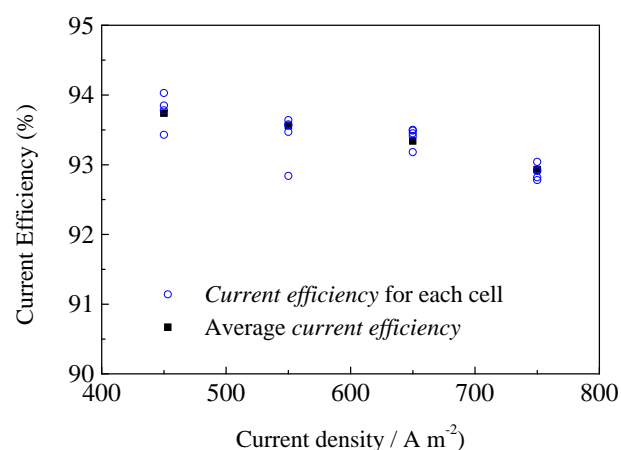


FIG. 8 CURRENT EFFICIENCY AS A FUNCTION OF CURRENT DENSITY AT 0.4 m/L Ni

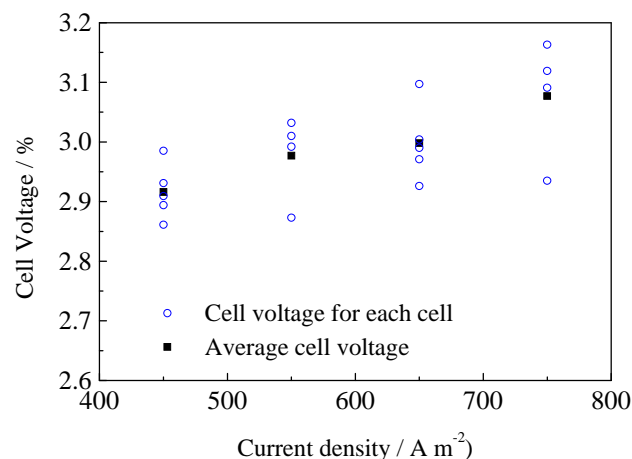


FIG. 9 AVERAGE CELL VOLTAGE AS A FUNCTION OF CURRENT DENSITY AT 0.4 m/L Ni

With increasing current density from 450 to 550 and 650 to 750 A/m^2 , the average cell voltage increased from 2.916 to 2.977 and 2.988 to 3.077 V (Fig. 9), i.e. the average cell voltages at 550, 650 and 750 A/m^2 were 2.09%, 2.81% and 5.52% higher than that at 450 A/m^2 , respectively, due to the larger cathodic, anodic polarization and IR drop at a higher current density. The energy consumption increased from 2.55 to 2.61 and 2.62 to 2.71 kWh/kg Zn.

A recommended current density was 650 Am^{-2} since the zinc mass deposit can significantly be increased and the energy consumption increases slightly. At a higher current density, the zinc deposit mass can only increase slightly while the energy consumption increases significantly. Further evaluation needs to consider the following factors: cell temperature, electrolyte cooling and acid evaporation.

Polarization Investigation

To further understand the effects of nickel concentration and current density on zinc electrowinning, cyclic voltammetry and linear polarization were conducted.

The cyclic voltammograms on aluminum cathodes at different nickel concentrations are shown in Fig. 10a. The peaks around -0.9 and -1.0 V vs Ag/AgCl were rescaled in Y-axis and shown in Fig. 10b to further depict the difference between these curves. The forward scan in the electrolyte without nickel revealed a flattened peak around -1.02V due to the hydrogen evolution. It was stimulated by the iron impurities contained in the aluminum substrate on which the potential of hydrogen evolution was lower than the potential on pure aluminium [Brennon et al., 1987; Stenfanov and Ivanov, 2002]. Zinc deposition began at -1.12 V vs Ag/AgCl and the large anodic peak showed that this was the predominant process. After the complete zinc dissolution, a peak appeared at -0.89 V vs Ag/AgCl, due to the hydrogen evolution on the iron aggregates covered with nickel.

The peaks at -1.02 V vs Ag/AgCl in the forward scan in the electrolyte containing 0.4 and 4.0 mg/L Ni were slightly higher than that without nickel due to the faster hydrogen evolution on the nickel deposited on the cathode. The potential of hydrogen evolution on nickel is about 0.10 V lower than that on iron and 0.40 V lower than that on aluminium [Sharma, 1998]. The zinc deposition began at -1.12 V vs Ag/AgCl. The smaller anodic peak for the electrolyte containing 4.0 mg/L Ni indicated that the zinc deposition was accompanied with hydrogen evolution. After the complete zinc dissolution, cathodic peaks occurred at -0.89 V due to the hydrogen evolution on the iron aggregates covered with nickel. The peak for the electrolyte containing 0.4 mg/L Ni was slightly higher than that in the electrolyte without Ni while the peak in the electrolyte containing 4.0 mg/L Ni was much higher due to the faster hydrogen evolution because of

the deposition of more nickel.

The cathodic polarization curves on the aluminum cathode at different nickel concentrations are shown in Fig. 11. They were similar to those at the forward scan in the cyclic voltammograms shown in Fig. 10. With decreasing cathode potential from -1.15V to -1.23 V vs Ag/AgCl, a current shoulder appeared.

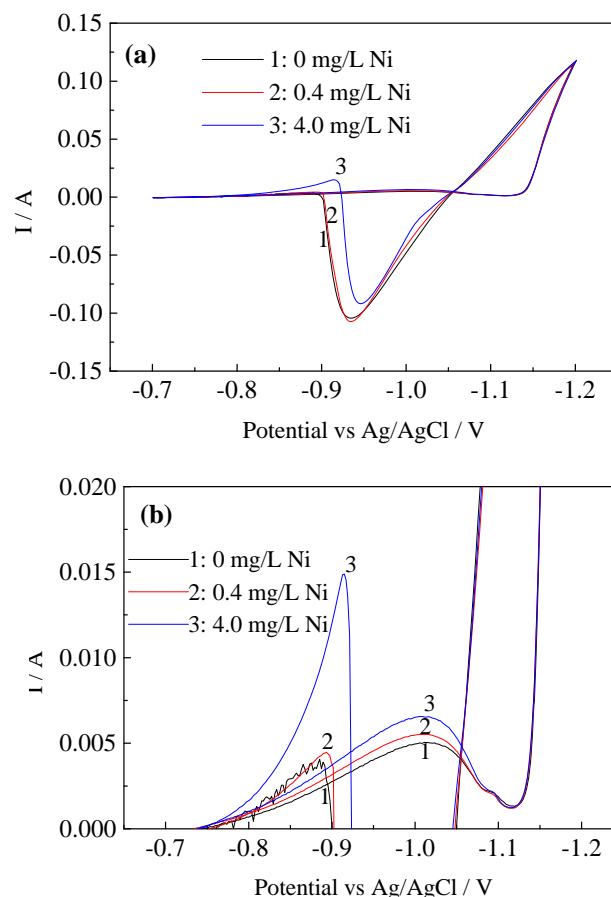


FIG. 10. (a) VOLTAMMOGRAM AND (b) RESCALED IN Y-AXIS OF (a) FOR ALUMINUM CATHODES AT DIFFERENT NICKEL CONCENTRATIONS AT A SWEEP RATE OF 0.5 mV s^{-1}

Fig. 12 shows the cathodic polarization curves on the zinc deposits obtained at 450 Am^{-2} . Compared with the polarization curves in Fig. 11, the Zn(II) reduction on the zinc deposit started at a potential about 50 mV more positive than that on the aluminum substrate, suggesting lower polarization of Zn(II) reduction on zinc. There was no current shoulder like that on the aluminium substrate shown in Fig. 11.

Comparison of Figs. 11 and 12, at a potential where a current shoulder appeared, indicated that the current density on the aluminium substrate was much higher than that on the zinc deposit due to a higher hydrogen evolution current density on the former. The aluminium substrate had better catalytic properties or

active sites for hydrogen evolution. As the active sites for hydrogen evolution on the aluminium substrate were gradually covered with zinc, the hydrogen evolution was progressively inhibited, resulting in a slow increase in the current density and then a current shoulder.

At a potential below -1.3 V vs Ag/AgCl, the current density on the aluminium substrate was close to that on the zinc deposit as the active sites for hydrogen evolution was completely covered by zinc.

From the above discussion, the addition of 0 to 0.4 mg/L Ni had very little effect on the cathodic polarization behaviour.

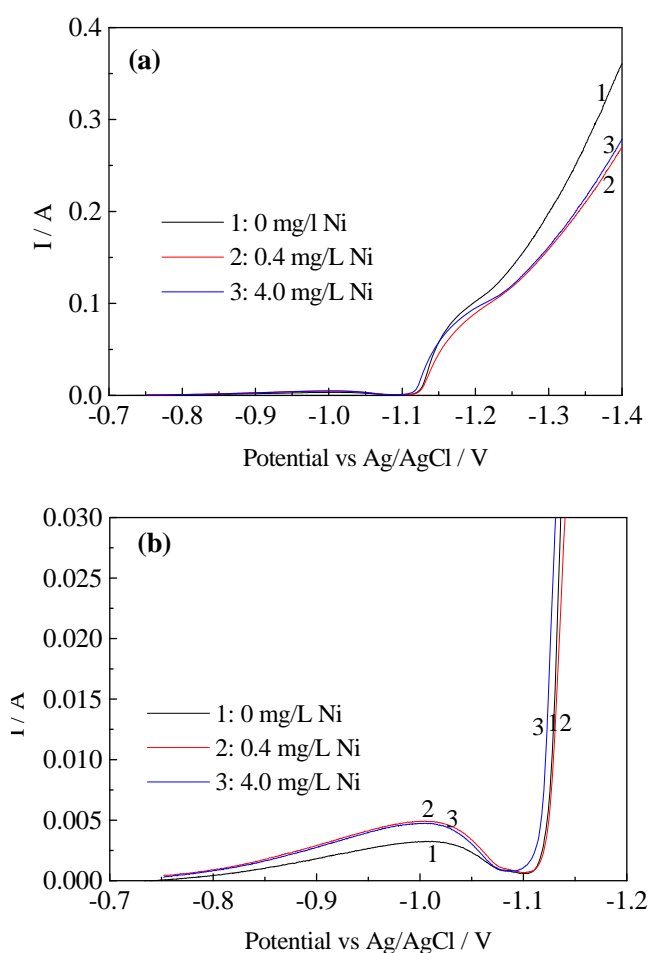


Fig. 11. (a) CATHODIC POLARIZATION CURVES AND (b) RESCALED IN Y-AXIS OF (a) ON ALUMINUM CATHODES IN ELECTROLYTES WITH DIFFERENT NICKEL CONTENTS AT A SWEEP RATE OF 0.5 mV s^{-1}

The polarization measurements were also conducted on the zinc deposits prepared at higher currents (550, 650 and 750 Am^{-2}). The current density for the preparation of the zinc deposits practically has very little effect on the polarization behaviour on the zinc deposit.

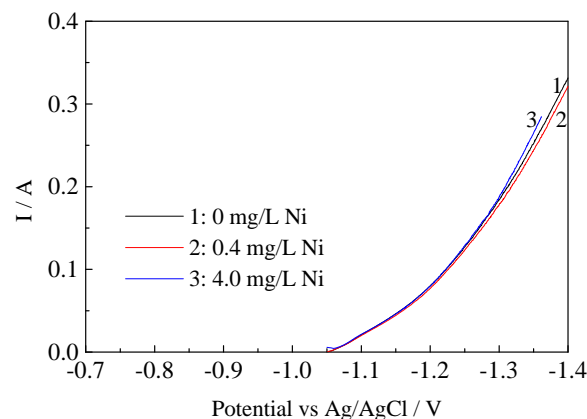


FIG. 12. CATHODIC POLARIZATION CURVES ON THE ZINC DEPOSITS IN THE ELECTROLYTE CONTAINING 0, 0.4 and 4.0 mg/L Ni.

Conclusions

The induction time for zinc deposit redissolution decreased with increasing nickel concentration. However, the zinc current efficiency prior to redissolution was not affected in the presence of up to 0.4 mg/L nickel.

In the presence of 0.4 mg/L Ni, with increasing current density from 450 to 550 and 650 to 750 Am^{-2} , the average induction time decreased from 49.3 to 44.62 and 44.41 to 40.3 hours, the zinc current efficiency decreased from 93.74 to 93.56 and 93.34 to 92.93%, and the energy consumption increased from 2.55 to 2.61 and 2.62 to 2.71 kWh/kg Zn . The average zinc deposit mass prior to zinc re-dissolution at 550, 650 and 750 Am^{-2} were 10.6, 32.6 and 35.6% greater than that at 450 Am^{-2} , respectively.

By comparison of zinc deposit masses prior to re-dissolution and energy consumption, a current density of 650 Am^{-2} is recommended for zinc electrowinning since at this current density, and the zinc deposit mass can be increased significantly while the energy consumption is increased slightly. The zinc electrowinning time should be controlled slightly below the average induction time. In some cases, if the nickel can not be removed to a satisfactory level economically, the current density can be adjusted to maximize zinc deposit masses.

The presence of up to 0.4 mg/L nickel had a little effect on the cathodic polarization behaviour.

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